Composite Higgs models with "the works"

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With the recent discovery of the Higgs boson, all elementary particles predicted by the Standard Model have now been observed.

But particle physicists remain troubled by several problems.

The hierarchy problem

Why is the Higgs mass only 126 GeV? Quantum effects naively suggest that $m_h \gtrsim 10^{16}$ GeV would be more natural.

Flavour hierarchies

Why is the top quark so much heavier than the electron?

Dark matter

What are the particles that make up most of the matter in the universe?

Gauge coupling unification

The three gauge couplings in the SM nearly unify, hinting towards a grand unified theory, but they don't quite meet.

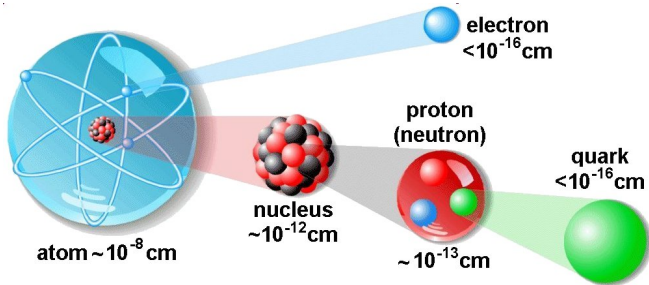## It feels like we might be missing something. . .

With the recent discovery of the Higgs boson, all elementary particles predicted by the Standard Model have now been observed.

However, there is a long history of things that looked like elementary particles turning out not to be

- Atoms
- Nuclei
- Hadrons

Splitting the atom

electron
$<10^{-16}$cm

proton
(neutron)

quark
$<10^{-16}$cm

nucleus
$\sim 10^{-12}$cm

atom $\sim 10^{-8}$ cm

$\sim 10^{-13}$cm

Can we really be sure we have reached the end of the line?

Perhaps some of the particles in the SM are actually composite.

The hierarchy problem

If the Higgs is composite it is shielded from quantum effects above the compositeness scale.

Flavour hierarchies

Compositeness in the fermion sector naturally gives $m_t \gg m_e$.

Dark matter

Many theories predict other composite states that are stabilised by global symmetries, just like the proton in the SM.

Gauge coupling unification

The SM gauge couplings unify much better if the Higgs and right-handed top quark are composite states.

This talk: part I

- Overview of how these ideas work
- Examples of how they can be realised in a single model

What do composite Higgs models look like in the UV?

This talk: part II

- Challenges faced by composite Higgs models in the UV
- Ways in which renormalisable UV completions may be found
- What a top-down approach tells us about low energy physics

Overview

The modern composite Higgs
Dark matter and unification
UV completions

Compositeness is not a new phenomenon.

Let's look at QCD. . .

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Most states have masses around the compositeness scale.

The QCD spectrum

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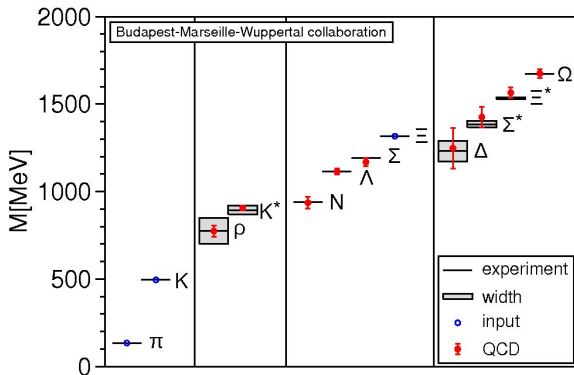
But we only see the Higgs at the LHC.

There has to be a little hierarchy between the Higgs mass and the compositeness scale.

This is expected if the Higgs is a Nambu-Goldstone boson of a spontaneously broken global symmetry.[1]

(cf. pions in QCD)

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[1]Kaplan, Georgi - 1984

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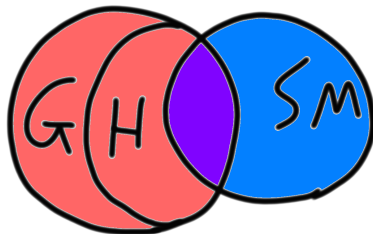
The standard framework is thus to assume the existence of a new, strongly-coupled sector with a global symmetry, G.

The strong sector confines at some compositeness scale, f, and G is spontaneously broken to a subgroup, H.

The Higgs is identified with NGBs from the spontaneous $G \rightarrow H$ symmetry breaking.

Hence H contains (part of) the SM gauge group.

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Typical group structure

Example[1]

$$G = SO(5) \qquad H = SO(4) \sim SU(2)_L \times SU(2)_R$$

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[1] Agashe, Contino, Pomarol 2004

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Problem: strongly coupled physics is hard!

Fortunately the details of the strong sector do not have to be specified if we are only interested in low-energy physics.

Low-energy theorems determine the physics of the NGBs from symmetries alone.

A simpler, effective theory can be used instead.[1]

(cf. the chiral Lagrangian for pion physics in QCD)

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[1]Callan, Coleman, Wess, Zumino 1969

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The full Lagrangian looks like

$$\mathcal{L}_{\text{elementary}} + \mathcal{L}_{\text{strong}} + \sum A^\mu \Omega \mathcal{J}_\mu + \sum \psi \lambda_\psi \mathcal{O}_\psi$$

Ω and λ are projectors, projecting G representations in the strong sector onto SM representations.

They also act as spurions, explicitly breaking $G \times G_{\text{SM}}$ to G_{SM}.

The Higgs becomes a pseudo-NGB, getting a mass and potential.

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Integrate out the strong sector to get the effective theory.

The Higgs potential is generated by loops involving Ω, λ and elementary SM fields that explicitly break G.

Some one-loop contributions to the Higgs potential

$\Omega \Sigma(h) \Pi(p) \Omega$ $\mathcal{A}$ $\lambda_\psi \Sigma(h) \Pi(p) \lambda_\psi^*$ ψ
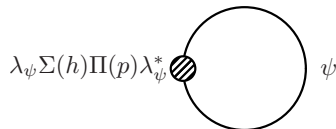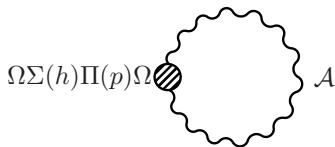
Σ is derived purely from group theory.

Π is a momentum-dependent form factor from the strong sector.

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Solution: the hierarchy problem

The extra momentum dependence from Π renders these loops finite - there are no divergences in the composite Higgs potential.[1]

The electroweak scale is naturally of order the compositeness scale suppressed by a loop factor.

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[1]Marzoccaa, Serone, Shu 2012; Pomarol, Riva 2012

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To get masses chiral fermions must couple to the Higgs, so they must couple to the strong sector

$$\mathcal{L} \supset [\psi \lambda_\psi \mathcal{O} + \psi^c \lambda_{\psi^c} \mathcal{O}^c] + g_\rho \left[\mathcal{O}\bar{\mathcal{O}} + \mathcal{O}^c \bar{\mathcal{O}}^c + \bar{\mathcal{O}}\bar{\mathcal{O}}^c \mathcal{O}_h \right]$$

Integrating out $\mathcal{O}$ and $\mathcal{O}^c$ to get the effective theory gives

$$\mathcal{L} \supset \frac{\lambda_\psi \lambda_{\psi^c}}{g_\rho} \psi \psi^c \mathcal{O}_h$$

Hence a Yukawa coupling is generated with $y_\psi = \lambda_\psi \lambda_{\psi^c} / g_\rho$.

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We want the top-quark Yukawa coupling

$$y_t = \frac{\lambda_t \lambda_{t^c}}{g_\rho}$$

to be large.

The easiest way to do this is to choose $\lambda_{t^c} = g_\rho$.

Hence the right-handed top quark becomes part of the strong sector, i.e. it is fully composite.

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Conversely, a small electron Yukawa coupling follows from coupling e to a higher dimension operator and allowing a long RG flow

$$\mathcal{L} \supset e\lambda_e \mathcal{O}_e \quad \implies \quad \lambda_e \sim \left(\frac{f}{M}\right)^{\dim \mathcal{O}_e - \frac{5}{2}}$$

with $M \gg f$.

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Ultimately, differences in operator dimensions are exponentiated

$$\frac{y_e}{y_t} \sim \left(\frac{f}{M}\right)^{\dim \mathcal{O}_e - \dim \mathcal{O}_t}$$

so small hierarchies in operator dimensions give large hierarchies in Yukawa couplings.

Solution: flavour hierarchies

Order-one differences in operator dimensions are natural in strongly coupled theories.

$\dim \mathcal{O}_e > \dim \mathcal{O}_t$ and $M \gg f$ reproduces the hierarchies seen in the SM fermion masses.[1]

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[1] Kaplan 1991; Gherghetta, Pomarol 2000

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Dark matter I
Gauge coupling unification and dark matter II
Putting it all together

Dark matter, option I: pNGB dark matter

Use the global symmetry already present in the strong sector.

Consider an $O(6) \to O(5)$ symmetry breaking pattern in the strong sector

- Five broken generators $\implies$ one Higgs doublet + one singlet
- Singlet charged under unbroken parity contained in $O(6)$

Solution: dark matter

The extra pNGB gives rise to composite scalar dark matter.[1]

(other possibilities exist for different choices of G and H)

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[1] Frigerio, Pomarol, Riva, Urbano 2012

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Putting it all together

Composite states couple most strongly to other composite states.

Thus composite scalar dark matter couples strongly to the composite Higgs.

pNGB dark matter is a realisation of Higgs-portal dark matter.

Its mass is usually similar to that of the Higgs.

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Gauge coupling unification in the SM: $\Delta\alpha_i^{-1} \equiv \alpha_i^{-1} - \alpha_2^{-1}$

Unification is close but the couplings do not quite meet.

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How does unification work in composite models?

To accommodate a composite Higgs we need

$$SU(2)_L \times U(1)_Y \subset H \subset G$$

The simplest way to extend to a GUT is to embed a simple GUT group in H, e.g.

$$SU(5) \subset H \subset G$$

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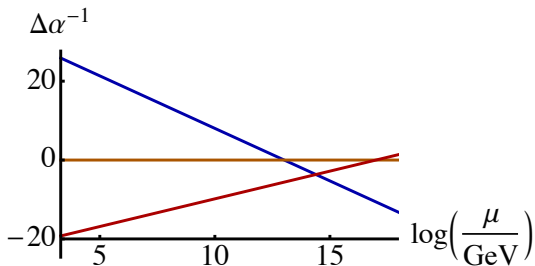Putting it all together

GUT group structure

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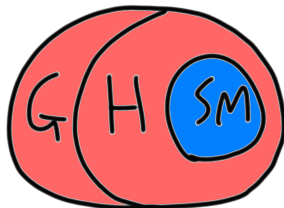
All composite states come in complete multiplets of the strong
sector's unbroken global symmetry, H.

Because $SU(5) \subset H$ all composite states automatically come in
complete GUT multiplets too.

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The light composite states are

- The Higgs
- The right-handed top quark

In minimal $SU(5)$ there are therefore additional composite states

- $h \longrightarrow \mathbf{5} = D \oplus T$
- $t^c \longrightarrow \mathbf{10} = t^c \oplus \tilde{q} \oplus \tilde{e}^c$

Why don't we see them?

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The scalar colour triplet is heavier than the Higgs as $\alpha_3 \gg \alpha_{2,1}$.

The exotic composite fermions pair up with exotic elementary fermions, χ, to get a Dirac mass at the compositeness scale

$$\mathcal{L} \supset \chi \lambda_\chi \mathcal{O}_t \quad \Longrightarrow \quad m_\chi = \lambda_\chi f$$

These mass eigenstates will be referred to as top companions.

To retain a massless right-handed top quark, we only include Dirac partners for the other components of the multiplet

$$t^c \longrightarrow t^c \oplus \tilde{q} \oplus \tilde{e}^c \quad \Longrightarrow \quad \chi = \tilde{q}^c \oplus \tilde{e}$$

(note: 'doublet-triplet' splitting moved to the fermion sector)

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Now we can observe the effect on the SM gauge couplings.[1]

First move all composite states from the elementary sector to the strong sector

$$\alpha(\mu) = \text{SM} - \{H, t^c\} + \text{strong sector} + \text{elementary exotics}$$

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[1]Agashe, Contino, Sundrum - 2005

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The exact strong sector contribution cannot be calculated without a UV completion.

But all composite states come in complete GUT multiplets so the contribution is always universal.

Therefore

$$\alpha_i(\mu) - \alpha_j(\mu) = \text{SM} - \{H, t^c\} + \text{elementary exotics}$$

The elementary exotic fermions form a complete GUT multiplet without a right-handed top, so

$$\alpha_i(\mu) - \alpha_j(\mu) = \text{SM} - \{H, t^c, \bar{t}^c\}$$

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Gauge coupling unification in composite models
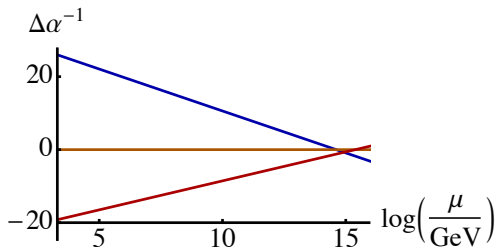
For $m_T \sim m_\chi \sim 1$ TeV unification is greatly improved.

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Postdiction of α_3: $\delta_3 \equiv [\alpha_3^{\text{th}}(M_Z) - \alpha_3^{\text{ex}}(M_Z)]/\alpha_3^{\text{ex}}(M_Z)$
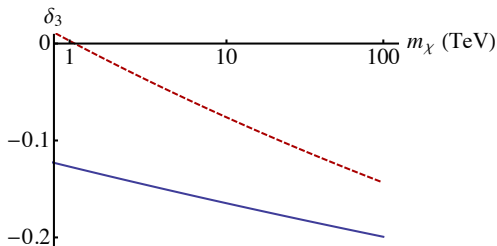
Unification remains reasonable for m_T, m_χ up to about 100 TeV.

A 5D calculation gives even better results (if you believe it).

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Solution: gauge coupling unification

If the Higgs and right-handed top quark are composite, unification of the SM gauge couplings is greatly improved.

This holds for compositeness scales up to about 100 TeV.

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Dark matter, option II: top companion dark matter

In composite GUTs there is another dark matter candidate.

It is closely related to the problem of proton decay.

(cf. SUSY)

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Strong sector interactions generically lead to effective operators of the form

$$\frac{\sqrt{y_i y_j y_k y_l}}{f^2} \psi_i \psi_j \psi_k \psi_l$$

These mediate proton decay; the above suppression is not enough.

A symmetry must be imposed to forbid these operators.

The simplest option is to assume that the strong sector respects baryon number.

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Take an $SO(10)$ GUT with a composite right-handed top quark.

The right-handed top quark GUT multiplet contains composite states

$$(t^c \oplus \tilde{q} \oplus \tilde{e}^c \oplus \tilde{b}^c \oplus \tilde{l} \oplus \tilde{\nu}^c)_{-\frac{1}{3}}$$

With $U(1)_B$, there is a new, unbroken Z_3 symmetry: baryon triality

$$(3B - n_c) \mod 3$$

No SM state has Z_3 charge, but $\tilde{l}$ and $\tilde{\nu}^c$ do.

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If $\tilde{l}$ and $\tilde{\nu}^c$ are the lightest Z_3-charged states they act as dark matter.[1]

(cf. neutralino dark matter)

Solution: dark matter

Top companions can act as composite fermion dark matter.

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[1] Agashe, Servant 2005

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The simplest composite GUT with top companion dark matter is the $SO(10)$ GUT group just discussed.[1]

It predicts neutralino-like dark matter.

Problems with $SO(10)$

- It is a large group $\implies$ many exotics
- $SO(11) \rightarrow SO(10)$ is hard to realise in the UV (see later)
- The scalar colour triplet can be cosmologically troubling

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[1]Agashe, Servant 2005; Frigerioa, Serra, Varagnolo 2011

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$SO(10)$ was originally chosen as it contains a custodial symmetry to prevent large corrections to electroweak precision observables.

But constraints from the flavour sector still need to be addressed.

Without special flavour structure we need $f \gtrsim 10$ TeV due to

- Observables in the Kaon sector[1]
- $e \to \mu$ and $\mu \to e\gamma$ processes[2]

Plus the LHC hasn't seen any exotic states yet.

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[1]Bellazzini, Csaki, Serra 2014
[2]Agashe, Blechman, Petriello 2006; Keren-Zur, Lodone, Nardecchia, Pappadopulo, Rattazzi 2012

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The simple solution: take $f \gtrsim 10$ TeV.

The price: a tuning in the Higgs VEV worse than $v^2/f^2 = 0.06\%$.

However, the hierarchy problem remains mostly solved.

(cf. mini-split SUSY)

Gauge coupling unification imposes an upper limit $f \lesssim 100$ TeV.

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Precision electroweak and flavour constraints are trivially satisfied.

$\implies$ there is no need for a custodial symmetry.

What is the minimal model with an $SU(5)$ GUT group?

We also want pNGB dark matter; top companions are too heavy.

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The unnatural composite Higgs[1]

- Symmetry breaking pattern $U(7) \rightarrow U(6) \times U(1)$
- $SU(5) \subset U(6)$
- 12 NGBs: a complex **5** and a complex singlet, S, of $SU(5)$
- S charged under a linear combination of the $U(1)$s in H
- $U(1)$s in H mix with baryon number to render singlet stable

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[1] JB, Gherghetta, Ray, Spray 2014

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Exotic pNGB states

$$T \in (\mathbf{3}, \mathbf{1})_{-\frac{1}{3}} \qquad\qquad S \in (\mathbf{1}, \mathbf{1})_0$$

These are determined by the symmetry breaking pattern.
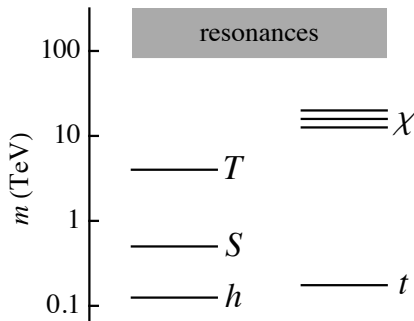
They could be produced at the LHC.

Exotic top companion fermions

$$\tilde{q}^c \in (\bar{\mathbf{3}}, \mathbf{2})_{-\frac{1}{6}} \quad \tilde{e} \in (\mathbf{1}, \mathbf{1})_{-1} \quad \tilde{d}^c \in (\bar{\mathbf{3}}, \mathbf{1})_{\frac{1}{3}} \quad \tilde{l} \in (\mathbf{1}, \mathbf{2})_{-\frac{1}{2}}$$

These are determined by the model's matter embedding.

They would be produced at a 100 TeV collider.

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Typical spectrum

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Dark matter I
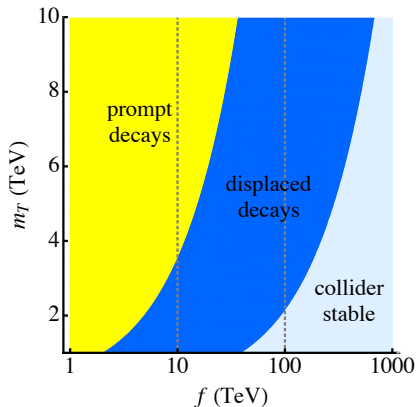Gauge coupling unification and dark matter II
Putting it all together

The scalar colour triplet only decays through the dimension-six operator

$$\mathcal{L} \supset \frac{1}{24\pi^2 f^2} |\lambda_{b^c}||\lambda_\nu||\lambda_\tau| S^2 (T^\dagger t^c b^c)$$

due to residual symmetries.

This leads to displaced vertices when it is produced at colliders.

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Colour triplet lifetime

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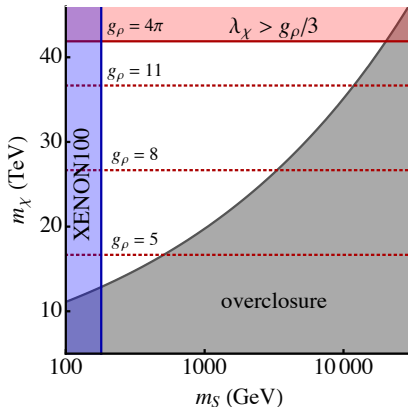The scalar singlet acts as Higgs-portal dark matter with

$$\mathcal{L} \supset \frac{\lambda_\chi^4}{4\pi^2}|S|^2|D|^2$$

(recall that $m_\chi = \lambda_\chi f$)

It must

- annihilate efficiently enough to not overclose the universe
- be consistent with direct detection limits
- be consistent with λ_χ being a perturbation to the strong sector

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Dark matter parameter space, $f = 10$ TeV

Overview

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The Higgs sector
The top quark Yukawa coupling
New observables from the UV

Ideally, a composite Higgs theory should arise from a theory of gauge fields and fermions only.

Including elementary scalars just shifts the hierarchy problem elsewhere.[1]

Questions

- What symmetry breaking patterns can be realised?
- How can we generate the top quark Yukawa coupling?

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[1] e.g. to a supersymmetric UV completion: Caracciolo, Parolini, Serone 2013

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New observables from the UV

Let's start with the original global symmetry group, G

- G should be derived from an exchange symmetry
- Fermions are complex objects
- $\implies SU(N_f)$ groups are favoured

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G is then broken to H by a fermion condensate, $\langle \psi\psi' \rangle$.

Symmetry breaking patterns like $SO(N_f) \rightarrow SO(N_f - 1)$ require $\langle \psi\psi' \rangle$ to be in the fundamental representation.

Thus ψ and ψ' need to be in different representations.

How do we stop $\psi\psi$ and $\psi'\psi'$ condensates forming and wrecking the symmetry breaking pattern?

Symmetry breaking induced by a unique condensate $\langle \psi\psi \rangle$ in a two-index representation of G is much easier to arrange.

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Preferred composite Higgs models from a UV perspective[1]

- G should be an $SU(N_f)$ symmetry
- Symmetry breaking should be induced by a unique condensate in a two-index representation of G

Disfavoured models

- The minimal $SO(5) \rightarrow SO(4)$ model
- The $SO(11) \rightarrow SO(10)$ GUT model

Favoured models

- The next-to-minimal $SU(4) \rightarrow Sp(4)$ model[2]
- The $U(7) \rightarrow U(6) \times U(1)$ GUT model

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[1] JB, Gherghetta, Ray 2013; Ferretti, Karateev 2013
[2] Gripaios, Pomarol, Riva, Serra 2009

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An explicit example of a UV completion for the Higgs sector is an $Sp(2N_c)$ gauge theory with four flavours of fermion

$\implies$ a global $SU(4)$ symmetry.

The theory is asymptotically free and confines in the IR.[1]

The fermion condensate $\langle \psi\psi \rangle$ is in the antisymmetric representation of $SU(4)$.

Hence $SU(4) \rightarrow Sp(4)$.[2]

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[1]Coleman, Witten 1980; Peskin 1980
[2]Galloway, Evans, Luty, Tacchi 2010

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The top quark Yukawa coupling
New observables from the UV

When the Higgs is composite what does the top quark Yukawa coupling look like in the UV?

Either there is a direct coupling

$$\mathcal{L} \supset tt^c \psi\psi$$

or the top quark is (partially) composite and there is a mixing term

$$\mathcal{L} \supset t\mathcal{O}_t$$

If the composite operator, $\mathcal{O}_t$, is made purely out of fermions it must be at least a three-fermion operator.

In both cases the UV completion contains four-fermion operators.

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New observables from the UV

Gauge theories with four-fermion operators have been studied before: gauged NJL models.[1]

Surprisingly, these models appear to be renormalisable.

Two approaches suggest this

- Self consistent solutions to the Schwinger-Dyson equations in the ladder approximation[2]
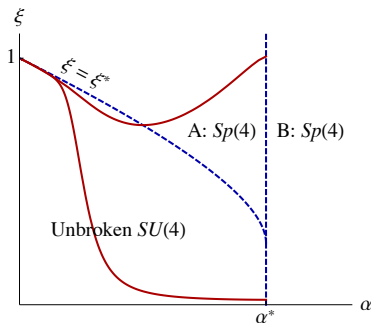- Analyses of Wilsonian effective potentials[3]

Both predict a UV 'fixed' point for the four-fermion coupling.

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[1] Nambu, Jona-Lasinio 1961
[2] Bardeen, Leung, Love 1986; Kondo, Mino, Yamawaki 1989
[3] Aoki, Morikawa, Sumi, Terao 1999

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RG flows in a gauged NJL model for $SU(4) \rightarrow Sp(4)$

α is the strong sector gauge coupling, ξ the four-fermion coupling.

A critical line with $\beta_\xi = 0$ separates phases of broken and unbroken global symmetry.

Near the critical line $\psi\psi$ has a large anomalous dimension.

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New observables from the UV

Explicit realisations of this idea allowing for a fully composite right handed top have been constructed.[1]

The prospects of building a complete model of flavour in this framework are good.

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[1] JB, Gherghetta, Ray 2013; Ferretti 2014

The modern composite Higgs   The Higgs sector
Dark matter and unification   The top quark Yukawa coupling
UV completions   New observables from the UV

We have already seen that considerations of the UV completion clearly favour some composite Higgs models over others.

What else can we learn?

The modern composite Higgs
Dark matter and unification
UV completions

The Higgs sector
The top quark Yukawa coupling
New observables from the UV

Some things we can gain from the UV completion

Precise predictions for the resonance spectrum (cf. QCD mesons)

The ability to calculate RG flows

- Check SM gauge coupling unification[1]
- Check for Landau poles

Better understanding of non-perturbative effects, e.g. WZW terms[2]

- Predictions for pNGB decays (cf. $\pi \to \gamma\gamma$ in QCD)
- The Skyrmion spectrum (cf. QCD baryons)

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[1]Ferretti 2014

[2]Jones *in preparation*

Summary

Composite Higgs models can comfortably accommodate

- the SM flavour hierarchies
- dark matter (scalar or fermion)
- SM gauge coupling unification

A simple model providing all three is based on the symmetry breaking pattern $U(7) \rightarrow U(6) \times U(1)$.

The model has a split spectrum and predicts a metastable scalar colour triplet, decaying via displaced vertices at colliders.

Many composite Higgs models have excellent prospects for UV completion.

The UV completions really are complete, and can tell us useful things about low energy physics.